EUROPEAN PATENT APPLICATION

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(54) **Heart-related parameters monitoring apparatus.**

(57) A non-invasive method, and an apparatus, for determining heart-related parameters in patients. The method and apparatus determine pulse pressure, time constant of the arterial system, systolic and diastolic pressure, peripheral resistance, cardiac output and mean arterial blood pressure.

FIG.1
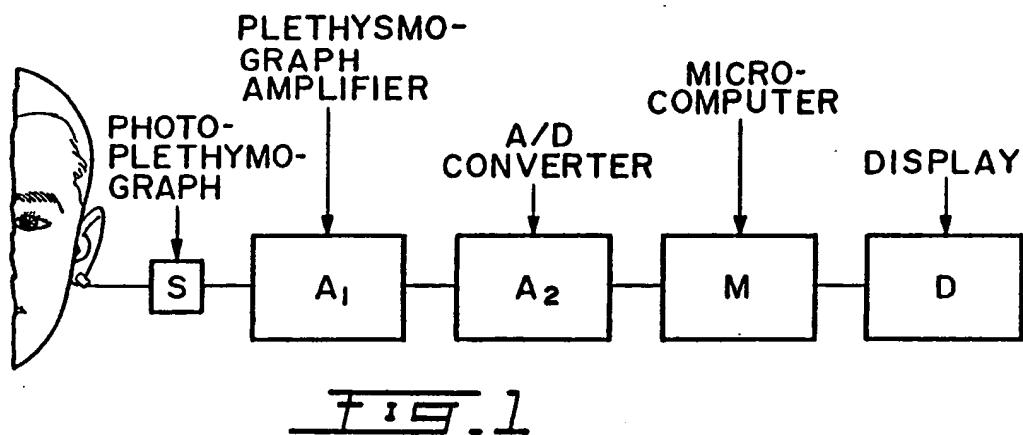
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HEART-RELATED PARAMETERS MONITORING APPARATUS

BACKGROUND OF INVENTION

Field of the Invention

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The invention relates to a non-invasive method of measuring arterial blood pressure and cardiac output. The invention also relates to an apparatus for carrying out the method.

10 Description of Prior Art

Non-invasive methods an apparatus for measuring arterial blood pressure and cardiac output are known in the art. One such method and apparatus is illustrated in U.S. Patent 4,030,485, Warner, issued June 21, 1977. A second such method and apparatus is taught in U.S. Patent 4,418,700, Warner, issued December 15 6, 1983. The present invention constitutes an improvement and refinement of the method and apparatus as taught in the latter patent.

SUMMARY OF INVENTION

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The invention relates to a non-invasive method, and an apparatus for determining heart-related parameters in patients. The method and apparatus determine pulse pressure, time constant of the arterial system, systolic and diastolic pressure, peripheral resistance, and cardiac output and mean arterial blood pressure.

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BRIEF DESCRIPTION OF DRAWINGS

The invention will be better understood by an examination of the following description together with the 30 accompanying drawings in which:

FIGURE 1 is a block diagram of the apparatus for carrying out the inventive method;
FIGURE 2 is a typical sensor output of the system as illustrated in Figure 1;
FIGURE 3 illustrates arterial blood pressure pulses;
FIGURES 4, 4a and 4b illustrate a blood volume pulse;
35 FIGURE 5 illustrates a blood volume pulse and a blood pressure pulse to illustrate the ratio g; and
FIGURE 6 is a simplified flowchart for a computer program for performing calculations in accordance with the invention.

DESCRIPTION OF PREFERRED EMBODIMENTS

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As seen in Figure 1, an apparatus in accordance with the invention comprises a volume sensor such as a photo-electric plethysmograph S, an amplifier A_1, an analog to digital converter A_2, a microcomputer M and a display device D. The plethysmograph sensor S is attached to, for example, the earlobe of a subject. 45 The sensor could also be attached to other suitable parts of the body such as the forehead, fingertips or toes.

As is known, the plethysmograph detects changes in blood volume of the region to which it is attached. A typical sensor output signal is shown in Figure 2. As seen in Figure 2, the output signal has a pulsating component and a DC component.

50 The output of the sensor is applied to the plethysmograph amplifier A_1 where it is amplified and filtered and the DC component is discarded. The output of A_1 has a DC component, but this is not directly related to the sensor DC component.

The output of A_1 is fed to the analog to digital (A/D) converter A_2 which digitizes the signal. In a preferred embodiment, the sampling rate is 100 per second.

Microcomputer M accepts signals from A_2 and processes them according to the instructions it contains.

These instructions are schematically represented in the simplified flowchart of Figure 6.

The computer quantitites are then displayed on a CRT monitor D or other suitable display means.

5 ## THEORY

Arterial blood pressure pulses are shown in Figure 3. The shape of these curves vary according to the site where they are measured. The highest pressure reached during a cycle i is called the arterial systolic blood pressure, P_{si}. The lowest pressure reached during the same cycle is called the arterial diastolic blood 10 pressure, P_{di}. The pressure rise from P_{di} to P_{si} in the same cycle is the pulse pressure P_{pi}.

By definition $P_{si} - P_{di} = P_{pi}$ (1)

To find P_{pi}
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A plethysmographic pulse is shown in Figure 4. The minimum value at the beginning of the pulse is V_{imin}. The maximum value of the pulse is V_{imax}. As the pulse volume rises from V_{imin} to V_{imax}, the time rate of volume change reaches a maximum $\dot{V}_{imax}$ at time t_i $\dot{v}m$. The pulse volulme at time V_i $\dot{v}m$ is V_i $\dot{v}m$.

let
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$$\frac{V_{i\dot{v}m} - V_{imin}}{V_{imax} - V_{imin}} = \frac{\Delta V_{i\dot{v}m}}{\Delta V_i} = R_i \qquad (2)$$

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In addition to finding the values of V_i $\dot{v}m$ corresponding to $\dot{V}_{imax}$, see U.S. Patent 4,418,700, Warner, values of V_i $\dot{v}m$ are also found corresponding to $\dot{V}_{imax}$-1, $\dot{V}_{imax}$-2, ... $\dot{V}_{imax}$-k, where k is a function of $\dot{V}_{imax}$.

All of the values of V_i $\dot{v}m$ corresponding to the time rates of volume change lying between and including $\dot{V}_{imax}$ and $\dot{V}_{imax}$-k are averaged and used to compute ΔV_i $\dot{v}m$.

30 The average value of V_i $\dot{v}m$ is

$$\overline{V}_{i\dot{V}m} = \frac{\sum_1^{n0} V_{i\dot{v}_0 mn0} + \sum_1^{n1} V_{i\dot{v}_1 mn1} + \ldots + \sum_1^{nk} V_{i\dot{v}_k mnk}}{n0 + n1 + \ldots + nk}$$

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where
n0 = number of values of V_i $\dot{v}_0 m$ corresponding to $\dot{V}_{imax}$
n1 = number of values of V_i $\dot{v}_1 m$ corresponding to $\dot{V}_{imax}$-1
40 ... = ...
nk = number of values of V_i $\dot{v}_k m$ corresponding to $\dot{V}_{imax}$-k

$$k = \frac{\dot{V}_{imax}}{m} \quad \text{(integral values only)} + \ell$$
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m = constant ... a preferred value of m = 20
ℓ = constant ... a preferred value of ℓ = 1

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$$P_{pi} = K_{pp} \left(\frac{R_i - r_1}{(1 + r_2 - R_i)} \propto \right) \qquad (4a)$$

55 K_{pp} = constant determined by a first calibration
r_1 = constant ... preferably equal to 0
r_2 = constant ... preferably equal to 0
$0 \leq \alpha \leq 1$

R_i can now be defined, as per equation (2) above, but using the average value of $V_i \dot{v}_m$ so that equation (2) can be rewritten

let

$$\frac{\overline{V}_{i\dot{V}m} - V_{imin}}{V_{imax} - V_{imin}} = \frac{\Delta V_{i\dot{v}m}}{\Delta V_i} = R_i \qquad (2)$$

from Figure 4

$\Delta V'_i = \Delta V_i - \Delta V_i \dot{v}_m$

$$\frac{\Delta V'_i}{\Delta V_i} = R' = \frac{\Delta V_i - \Delta V_{i\dot{v}m}}{\Delta V_i} = 1 - \frac{\Delta V_{i\dot{v}m}}{\Delta V_i} - 1 - R_i$$

wherein $R'_i = 1 - R_i$
or $R_i = 1 - R_i$

No other calibration should be required with different subjects. However, if desired, K_{pp} can be determined for each subject.

To find mean blood pressure

The mean blood pressure P_{mi} during a cycle i is given by

$$P_{mmi} = K_4 \left[\frac{\Delta V_i}{\Delta \dot{V}_{imax}} \right]^{-b_3} \qquad (5)$$

$P_{mi} = P_{mmi} + P_0$ (6)
b_3 = exponent ... the preferred value of b_3 is equal to 0.5
K_4 = constant determined at calibration for each subject. It is only necessary to find this constant once for each subject. The measurements carried out at different times on the same subject do not require separate calibration
P_0 = constant ... preferred 25 mmHg
$\Delta \dot{V}_{imax}$ = maximum time rate of change of $\Delta V_i = \dot{V}_{imax}$
$P_{si} = P_{mi} + (1-g_i)P_{pi}$ (7)
where

$$g_i = \frac{\Delta V_{iAV}}{\Delta V_i} -$$

ΔV_{iAV} = average value of ΔV_i over the time interval T_i
$P_{di} = P_{si} - P_{pi}$ (8)
The variable g_i can take on a constant value g_0 whose preferred value is 0.333.
Alternatively, mean blood pressure can be determined using the following expression:

$$P_{mmi} = \left[K_4 \; \frac{\Delta V_i}{\Delta V_{imax}[G(t)]} \right]^{-b_3} \qquad (5')$$

$$= K_4 \left(\frac{1}{r_i} \right)^{-b_3}$$

(for definition of r_i, see equation (10) below)
where
G(t) = a function of t,
in a particular case,

$$G(t) = \frac{\phi_c}{\phi_i}$$

$$\phi_c = \left(\frac{1}{\Delta t_c} \right)^y$$

$$\phi_i = \left(\frac{1}{\Delta t_i} \right)^y$$

$\Delta t_i = \Delta t'_{i\phi}$
$\Delta t_c = \Delta t$ at calibration $= \Delta t'_{i\phi c}$ (see Figure 4B)
where
T_c = T at calibration
t_c = t at calibration

$$\phi_c = \frac{T_c}{t_c} = \frac{T}{t}$$

at calibration
y = constant.
    The remainder of the terms in equation the same as similar terms in equation

Determination of Ratio R (Figure 4b)

    From Figure 4b, the ratio R is

$$R_i = \frac{\Delta V_{it}}{\Delta V_i}$$

where
ΔV_{it} = change in volume at predetermined time ti
ΔV_i = total volume change during cycle i
t_i = time such that $\Delta t_i = K_T \Delta t'_{i\phi}$
K_T = constant

Estimation of pulse pressure, PP

$$K_{100} \left(\frac{1 - e^{-K'_T kPP_i}}{1 - e^{-kPP_i}} \right) = R_i$$

where

PP_i = pulse pressure = P_s - P_d
P_s = systolic blood pressure
P_d = diastolic blood pressure
k = constant
K'_T = constant $\simeq K_T$
K_{100} = coefficient

In Figure 4B
$\Delta V'_i = \Delta V_i - \Delta V_{it}$

$$\frac{\Delta V'_i}{\Delta V_i} = \frac{\Delta V_i - \Delta V_{it}}{\Delta V_i} = 1 - \frac{\Delta V_{it}}{\Delta V_i} = 1 - R_i = R'_i$$

wherein from the above equation:

$$K_{100}\left(1 - \frac{1 - e^{-K_T kPP_i}}{1 - e^{-kPP_i}} \right) = 1 - R_i$$

$$K_{100}\left(\frac{1 - e^{-kPP_i} - (1 - e^{-K_T kPP_i})}{1 - e^{-kPP_i}} \right) = 1 - R_i$$

$$K_{100}\left(\frac{- e^{-kPP_i} + e^{-K_T kPP_i}}{1 - e^{-kPP_i}} \right) = 1 - R_i$$

multiply numerator and denominator by e^{kPP_i}

$$K_{100}\left(\frac{-1 + e^{kPP_i} e^{-K_T kPP_i}}{e^{kPP_i} - 1} \right) = 1 - R_i$$

$$K_{100}\left(\frac{e^{kPP_i(1-K_T)} - 1}{e^{kPP_i} - 1} \right) = 1 - R_i = R'_i$$

Determination of r

From Figure 4

$$r_i = \frac{\dot{V}_{i\,max}}{\Delta V_i}\; G(t)$$

where

$\dot{V}_{i\,max}$ = maximum time rate of volume increase in cycle i

ΔV_i = total volume increase during cycle i

From Figure 4b

$$r = \frac{\dot{V}_{it}}{\Delta V_i}\; G(t)$$

where

$\dot{V}_{it}$ = time rate of increase of volume V_{it} at time t_i

ΔV_i = total volume increase of volume during cycle i

Estimation of Mean Blood Pressure

1) $P'_{mi} = K_1 r_{ic}^a$

where

K_1 = calibration constant

$$P'_{mi} = \frac{P_s + P_d}{2} - P_o$$

P_{si} = systolic blood pressure, in cycle i

$$P_{mi} = \frac{P_s + P_d}{2}$$

P_{di} = diastolic blood pressure, in cycle i

a = constant

P_o = constant

2) $e^{kP_{mi}} = k_2 r_{ic}^b$

where

K_2 = constant (calibration)

b = constant

$$K_3 \left(\frac{e^{-k(P_{mo}-j\emptyset_{1i})} - e^{-k(P_{mo}+j\emptyset_{2i})}}{e^{-k(P_{mo}-\emptyset_{1i})} - e^{-k(P_{mo}+\emptyset_{2i})}} \right) = r_i \qquad (9)$$

where

P_{mo} = constant at calibration

$\emptyset_{1i} + \emptyset_{2i} = PP_i$ = pulse pressure during cycle i

k = constant

j = constant

K_3 = coefficient

solve equation by making LHS = RHS by varying $\emptyset_{1i}$ and $\emptyset_{2i}$ ($\emptyset_{2i} = PP_i - \emptyset_{1i}$)

then

$P_{si} = P_{mo} + \emptyset_{2i} + P_o$

$P_{di} = P_{mo} - \emptyset_{1i} + P_o$

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$$P_{mi} = \frac{P_{si} + P_{di}}{2}$$

P_o = constant

10 r_i = ratio of exponentials

K_3 = coefficient (variable or constant)

Correction for r_i

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$$r_i \text{ (corrected)} = r_{ic} = r_i \, e^{m(\emptyset_o - \emptyset_i)}$$

m = constant

$\emptyset_o$ = PP$_i$ at calibration

20 $\emptyset_i$ = current value of PP$_i$.

Equation (9) above is only one form which this particular equation can take. By simple mathematical manipulations, the invention may take two other forms as per (10) and (11) below. What follows is the manipulations as well as the two other forms of the equation:

As above noted

25 $\emptyset_{2i} + \emptyset_{1i} = PP_i = P_{si} - P_{di}$

$\emptyset_{2i} + \emptyset_{1i} = (P_{si} - P_o) - (P_{di} - P_o)$

Let $P'_{si} = P_{si} - P_o$

$P'_{di} = P_{di} - P_o$

$\emptyset_{2i} + \emptyset_{1i} = P'_{si} - P'_{di}$

30 add and subtract P_{mo} on RHS above

$\emptyset_{2i} + \emptyset_{1i} = P'_{si} - P_{mo} + P_{mo} - P'_{di}$ (A)

$\emptyset_{2i}$ and $\emptyset_{1i}$ can take on any values in satisfying the above equation (A)

Put $\emptyset_{2i} = P'_{si} - P_{mo}$

and $\emptyset_{1i} = P_{mo} - P'_{di}$ in equation (9)

35 then

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$$K_3 \left[\frac{e^{-k(P_{mo} - j(P_{mo} - P'_{di}))} - e^{-k(P_{mo} + j(P'_{si} - P_{mo}))}}{e^{-k(P_{mo} - (P_{mo} - P'_{di}))} - e^{-k(P_{mo} + (P'_{si} - P_{mo}))}} \right] = r_i \quad \ldots(10)$$

simplifying the denominator

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$$K_3 \left[\frac{e^{-k(P_{mo} - j(P_{mo} - P'_{di}))} - e^{-k(P_{mo} + j(P'_{si} - P_{mo}))}}{e^{-kP'_{di}} - e^{-kP'_{si}}} \right] = r_i \quad \ldots(11)$$

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To solve equation 11:

1) Set $P'_{di} = P'_{si} - PP_i$ and solve for P'_{si}

2) Set $P'_{si} = P'_{di} - PP_i$ and solve for P'_{di}

Although particular embodiments have been illustrated, this was for the purpose of describing, but not limiting, the invention. Various modifications, which will come readily to the mind of one skilled in the art, are within the scope of the invention as defined in the appended claims.

Claims

1. Apparatus for determining the magnitude of heart-related parameters in a patient; comprising:
means for detecting blood volume, and thereby blood volume variation, in said patient, and for providing a signal representative of said blood volume, and thereby said blood volume variation;
said means for detecting being attachable to said patient to thereby detect said blood volume, and thereby said blood volume variation;
said blood volume variation being cyclic in nature whereby said signal comprises a cyclic curve having, in each cycle of variation, a variable slope, a maximum amplitude representative of the maximum amount of blood volume, a minimum amplitude representative of the minimum amount of blood volume, a first time interval between said minimum amplitude and said maximum amplitude, a maximum rate of change of said signal being representative of the maximum rate of increase of blood volume, a second time interval between the minimum amplitude and the time of the maximum rate of change of said signal, a first difference in amplitude between said maximum amplitude and said minimum amplitude, a second difference in amplitude between the maximum amplitude and the amplitude at the time of maximum rate of change of said signal being representative of the difference in volume between the maximum amount of blood volume and the volume at the time of maximum rate of change of said blood volume, and a pulse repetition period;
means for measuring said maximum amplitude, said minimum aplitude, said maximum rate of change of said signal, said first difference, said second different, said first time interval, and said second time interval; and
means for calculating the magnitude of selected ones of said parameters, said means for calculating being connected to both said means for detecting and means for measuring;
wherein means for calculating calculates the magnitude of the pulse pressure parameter in accordance with the following expression:

$$P_{pi} = K_{pp} \left(\frac{R_{i1} + r_1}{(1 + r_2 - R_{i1})} \right)$$

wherein
P_{pi} = pulse pressure during cycle i
K_{pp} = constant determined by a first calibration
r_1 = constant
r_2 = constant

$$R_{i1} = \frac{\Delta V_{i \dot{V}m}}{\Delta V_i}$$

where
$\Delta V_{i \dot{V}m}$ = volume change at time t_{iVm} during cycle i corresponding to maximum rate of volume change, V_{imax}
ΔV_i = maximum volume change during cycle i cycle i
$\Delta t_{i \dot{V}m}$ = time interval from start of cycle i to time of maximum rate of volume change V_{imax}.

2. Apparatus for determining the magnitude of heart-related parameters in a patient; comprising:
means for detecting blood volume, and thereby blood volume variation, in said patient, and for providing a signal representative of said blood volume, and thereby said blood volume variation;
said means for detecting being attachable to said patient to thereby detect said blood volume, and thereby

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said blood volume variation;

said blood volume variation being cyclic in nature whereby said signal comprises a cyclic curve having, in each cycle of variation, a variable slope, a maximum amplitude representative of the maximum amount of blood volume, a minimum amplitude representative of the minimum amount of blood volume, a first time interval between said minimum amplitude and said maximum amplitude, a maximum rate of change of said signal being representative of the maximum rate of increase of blood volume, a second time interval between the minimum amplitude and the time of the maximum rate of change of said signal, a first difference in amplitude between said maximum amplitude and said minimum amplitude, a second difference in amplitude between the maximum amplitude and the amplitude at the time of maximum rate of change of said signal being representative of the difference in volume between the maximum amount of blood volume and the volume at the time of maximum rate of change of said blood volume, and a pulse repetition period;

means for measuring said maximum amplitude, said minimum aplitude, said maximum rate of change of said signal, said first difference, said second different, said first time interval, and said second time interval; and

means for calculating the magnitude of selected ones of said parameters, said means for calculating being connected to both said means for detecting and means for measuring;

wherein means for calculating calulates the magnitude of the mean arterial blood pressure, P_{mi} parameter in accordance with the following expression:

$P_{mi} = P_o + P_{mmi}$

$$P_{mmi} = K_4 \left[\frac{\Delta V_i}{\Delta \dot{V}_{imax} [G(t)]} \right]^{-b_3}$$

where

K_4 = constant determined for each subject

b_3 = constant

P_{mmi} = pseudo mean arterial blood pressure during cycle i

ΔV_i = maximum volume change during cycle i

$\Delta \dot{V}_{imax}$ = maximum time rate of change of ΔV_i

$= \dot{V}_{imax}$

where

$$G(t) = \frac{\phi_c}{\phi_i}$$

$$\phi_c = \left[\frac{1}{\Delta t_c} \right]^y$$

$$\phi_i = \left[\frac{1}{\Delta t_i} \right]^y$$

where

Δt_c = Δt at calibration = $\Delta t_{i\phi c}$

Δt_i = $\Delta t_{i\phi}$

y = constant.

3. Apparatus for determining the magnitude of heart-related parameters in a patient;
comprising;

means for detecting blood volume, and thereby blood volume variation, in said patient, and for providing a signal representative of said blood volume, and thereby said blood volume variation;

said means for detecting being attachable to said patient to thereby detect said blood volume, and thereby said blood volume variation;

said blood volume variation being cyclic in nature whereby said signal comprises a cyclic curve having, in each cycle of variation, a variable slope, a maximum amplitude representative of the maximum amount of blood volume, a minimum amplitude representative of the minimum amount of blood volume, a first time interval between said minimum amplitude and said maximum amplitude, a maximum rate of change of said signal being representative of the maximum rate of increase of blood volume, a second time interval between the minimum amplitude and the time of the maximum rate of change of said signal, a first difference in amplitude between said maximum amplitude and said minimum amplitude, a second difference in amplitude between the maximum amplitude and the amplitude at the time of maximum rate of change of said signal being representative of the difference in volume between the maximum amount of blood volume and the volume at the time of maximum rate of change of said blood volume, and a pulse repetition period;

means for measuring said maximum amplitude, said minimum aplitude, said maximum rate of change of said signal, said first difference, said second different, said first time interval, and said second time interval; and

means for calculating the magnitude of selected ones of said parameters, said means for calculating being connected to both said means for detecting and means for measuring;

wherein means for calculating calculates the magnitude of the systolic pressure (P_{si}) parameter in accordance with the following expression::

$P_{si} = P_{mi} + (1-g_o)P_{pi}$

wherein

g_o = constant.

4. Apparatus for determining the magnitude of heart-related parameters in a patient; comprising;

means for detecting blood volume, and thereby blood volume variation, in said patient, and for providing a signal representative of said blood volume, and thereby said blood volume variation;

said means for detecting being attachable to said patient to thereby detect said blood volume, and thereby said blood volume variation;

said blood volume variation being cyclic in nature whereby said signal comprises a cyclic curve having, in each cycle of variation, a variable slope, a maximum amplitude representative of the maximum amount of blood volume, a minimum amplitude representative of the minimum amount of blood volume, a first time interval between said minimum amplitude and said maximum amplitude, a maximum rate of change of said signal being representative of the maximum rate of increase of blood volume, a second time interval between the minimum amplitude and the time of the maximum rate of change of said signal, a first difference in amplitude between said maximum amplitude and said minimum amplitude, a second difference in amplitude between the maximum amplitude and the amplitude at the time of maximum rate of change of said signal being representative of the difference in volume between the maximum amount of blood volume and the volume at the time of maximum rate of change of said blood volume, and a pulse repetition period;

means for measuring said maximum amplitude, said minimum aplitude, said maximum rate of change of said signal, said first difference, said second different, said first time interval, and said second time interval; and

means for calculating the magnitude of selected ones of said parameters, said means for calculating being connected to both said means for detecting and means for measuring;

wherein means for calculating calculates the magnitude of the systolic pressure (P_{si}) parameter in accordance with the following expression:

$P_{si} = P_{mi} + (1-g_o)P_{pi}$

wherein:

$$g_i = \frac{\Delta V_{iAV}}{\Delta V_i}$$

P_{pi} = pulse pressure during cycle i

ΔV_i = represented by said first difference

ΔV_{iAV} = represented by the difference between said minimum amplitude and an amplitude equal to the

average value of a pulse in a cycle i.

5. Apparatus for determining the magnitude of heart-related parameters in a patient;
comprising;

means for detecting blood volume, and thereby blood volume variation, in said patient, and for providing a signal representative of said blood volume, and thereby said blood volume variation;

said means for detecting being attachable to said patient to thereby detect said blood volume, and thereby said blood volume variation;

said blood volume variation being cyclic in nature whereby said signal comprises a cyclic curve having, in each cycle of variation, a variable slope, a maximum amplitude representative of the maximum amount of blood volume, a minimum amplitude representative of the minimum amount of blood volume, a first time interval between said minimum amplitude and said maximum amplitude, a maximum rate of change of said signal being representative of the maximum rate of increase of blood volume, a second time interval between the minimum amplitude and the time of the maximum rate of change of said signal, a first difference in amplitude between said maximum amplitude and said minimum amplitude, a second difference in amplitude between the maximum amplitude and the amplitude at the time of maximum rate of change of said signal being representative of the difference in volume between the maximum amount of blood volume and the volume at the time of maximum rate of change of said blood volume, and a pulse repetition period;

means for measuring said maximum amplitude, said minimum aplitude, said maximum rate of change of said signal, said first difference, said second different, said first time interval, and said second time interval; and

means for calculating the magnitude of selected ones of said parameters, said means for calculating being connected to both said means for detecting and means for measuring;

wherein means for calculating calculates the magnitude of the arterial blood pressure, P_{mi} parameter in accordance with the following expression:

$P_{mi} = P_0 + P_{mmi}$

$$P_{mmi} = K_4 \left[\frac{\Delta V_i}{\Delta \dot{V}_{imax} [G(t)]} \right]^{-b_3}$$

where

K_4 = constant determined for each subject

b_3 = constant

P_{mmi} = pseudo mean arterial blood pressure during cycle i

ΔV_i = maximum volume change during cycle i

$\Delta \dot{V}_{imax}$ = maximum time rate of change of V_i = $\dot{V}_{imax}$

P_0 = constant

where

$G(t)$ = a function of t.

6. method for determining the magnitude of heart-related parameters in a patient;
comprising:

detecting blood volume, and thereby blood volume variation, in said patient and providing a signal representative of said blood volume, and thereby said blood volume variation;

said blood volume variation being cyclic in nature whereby said signal comprises a cyclic curve having, in each cycle of variation, a variable slope, a maximum amplitude representative of the maximum amount of blood volume, a minimum amplitude representative of the minimum amount of blood volume, a first time interval between said maximum amplitude and said minimum amplitude, a maximum rate of change of said signal being representative of the maximum rate of change of blood volume, a second time interval between the minimum amplitude and the time of the maximum rate of change of said signal, a first difference in amplitude between said maximum amplitude and said minimum amplitude, a second difference in amplitude between the maximum amplitude and the amplitude at the time of maximum change of rate of said signal being representative of the difference in volume between the maximum amount of blood volume and the volume at the time of maximum rate of change of said blood volume, and a pulse repetition period;

measuring said maximum amplitude, said minimum amplitude, said maximum rate of change of said signal, said first difference, said second difference, said first time interval, and said second time interval; and

calculating the magnitude of the pulse pressure parameter in accordance with the following expression:

$$P_{pi} = K_{pp} \left[\frac{R_{i1} - r_1}{(1 + r_2 - R_{i1})} \right]$$

wherein
P_{pi} = pulse pressure during cycle i
K_{pp} = constant determined by a first calibration
r_1 = constant
r_2 = constant

$$R_{i1} = \frac{V_{iVm}}{V_i}$$

where $\Delta V_i \ v_m$ = volume change at time t_{iVm} during cycle i corresponding to maximum rate of volume change, V_{imax}

ΔV_i = maximum volume change during cycle i
$\Delta t_i \ v_m$ = time interval from start of cycle i to time of maximum rate of volume change V_{imax}.

7. A method for determining the magnitude of heart-related parameters in a patient;
comprising:
detecting blood volume, and thereby blood volume variation, in said patient and providing a signal representative of said blood volume, and thereby said blood volume variation;
said blood volume variation being cyclic in nature whereby said signal comprises a cyclic curve having, in each cycle of variation, a variable slope, a maximum amplitude representative of the maximum amount of blood volume, a minimum amplitude representative of the minimum amount of blood volume, a first time interval between said maximum amplitude and said minimum amplitude, a maximum rate of change of said signal being representative of the maximum rate of change of blood volume, a second time interval between the minimum amplitude and the time of the maximum rate of change of said signal, a first difference in amplitude between said maximum amplitude and said minimum amplitude, a second difference in amplitude between the maximum amplitude and the amplitude at the time of maximum change of rate of said signal being representative of the difference in volume between the maximum amount of blood volume and the volume at the time of maximum rate of change of said blood volume, and a pulse repetition period; measuring said maximum amplitude, said minimum amplitude, said maximum rate of change of said signal, said first difference, said second difference, said first time interval, and said second time interval; and calculating the magnitude of the mean artial pressure P_{mi} in accordance with the following expression:
$P_{mi} = P_o + P_{mm_i}$

$$P_{mmi} = K_4 \left[\frac{\Delta V_i}{\Delta \dot{V}_{imax} [G(t)]} \right]^{-b_3}$$

where
K_4 = constant determined for each subject
b_3 = constant
P_{mmi} = pseudo mean arterial blood pressure during cycle i
ΔV_i = maximum volume change during cycle i
$\Delta \dot{V}_{imax}$ = maximum time rate of change of ΔV_i = $\dot{V}_{imax}$
where

$$G(t) = \frac{\phi_c}{\phi_i}$$

$$\phi_c = \left[\frac{1}{\Delta t_c}\right]^y$$

$$\phi_i = \left[\frac{1}{\Delta t_i}\right]^y$$

where

$\Delta t_c = \Delta t$ at calibration $= \Delta t_{\emptyset c}$

$\Delta t_i = \Delta t_{i\emptyset}$

y = constant.

8. A method for determining the magnitude of heart-related parameters in a patient; comprising:

detecting blood volume, and thereby blood volume variation, in said patient and providing a signal representative of said blood volume, and thereby said blood volume variation;

said blood volume variation being cyclic in nature whereby said signal comprises a cyclic curve having, in each cycle of variation, a variable slope, a maximum amplitude representative of the maximum amount of blood volume, a minimum amplitude representative of the minimum amount of blood volume, a first time interval between said maximum amplitude and said minimum amplitude, a maximum rate of change of said signal being representative of the maximum rate of change of blood volume, a second time interval between the minimum amplitude and the time of the maximum rate of change of said signal, a first difference in amplitude between said maximum amplitude and said minimum amplitude, a second difference in amplitude between the maximum amplitude and the amplitude at the time of maximum change of rate of said signal being representative of the difference in volume between the maximum amount of blood volume and the volume at the time of maximum rate of change of said blood volume, and a pulse repetition period; measuring said maximum amplitude, said minimum amplitude, said maximum rate of change of said signal, said first difference, said second difference, said first time interval, and said second time interval; and calculating the magnitude of the systolic pressure (P_{si}) parameter in accordance with the following expression:

$P_{si} = P_{mi} + (1-g_0)P_{pi}$

wherein

g_0 = constant.

9. A method for determining the magnitude of heart-related parameters in a patient; comprising:

detecting blood volume, and thereby blood volume variation, in said patient and providing a signal representative of said blood volume, and thereby said blood volume variation;

said blood volume variation being cyclic in nature whereby said signal comprises a cyclic curve having, in each cycle of variation, a variable slope, a maximum amplitude representative of the maximum amount of blood volume, a minimum amplitude representative of the minimum amount of blood volume, a first time interval between said maximum amplitude and said minimum amplitude, a maximum rate of change of said signal being representative of the maximum rate of change of blood volume, a second time interval between the minimum amplitude and the time of the maximum rate of change of said signal, a first difference in amplitude between said maximum amplitude and said minimum amplitude, a second difference in amplitude between the maximum amplitude and the amplitude at the time of maximum change of rate of said signal being representative of the difference in volume between the maximum amount of blood volume and the volume at the time of maximum rate of change of said blood volume, and a pulse repetition period; measuring said maximum amplitude, said minimum amplitude, said maximum rate of change of said signal, said first difference, said second difference, said first time interval, and said second time interval; and calculating the magnitude of the systolic pressure (P_{si}) parameter in accordance with the following expression:

$P_{si} = P_{mi} + (1-g_i)P_{pi}$

wherein:

$$g_i = \frac{\Delta V_{iAV}}{\Delta V_i}$$

P_{pi} = pulse pressure during cycle i

ΔV_l = represented by said first difference

ΔV_{iAV} = represented by the difference between said minimum amplitude and an amplitude equal to the average value of a pulse in a cycle i.

10. A method for determining the magnitude of heart-related parameters in a patient; comprising:

detecting blood volume, and thereby blood volume variation, in said patient and providing a signal representative of said blood volume, and thereby said blood volume variation;

said blood volume variation being cyclic in nature whereby said signal comprises a cyclic curve having, in each cycle of variation, a variable slope, a maximum amplitude representative of the maximum amount of blood volume, a minimum amplitude representative of the minimum amount of blood volume, a first time interval between said maximum amplitude and said minimum amplitude, a maximum rate of change of said signal being representative of the maximum rate of change of blood volume, a second time interval between the minimum amplitude and the time of the maximum rate of change of said signal, a first difference in amplitude between said maximum amplitude and said minimum amplitude, a second difference in amplitude between the maximum amplitude and the amplitude at the time of maximum change of rate of said signal being representative of the difference in volume between the maximum amount of blood volume and the volume at the time of maximum rate of change of said blood volume, and a pulse repetition period;

measuring said maximum amplitude, said minimum amplitude, said maximum rate of change of said signal, said first difference, said second difference, said first time interval, and said second time interval; and

calculating the magnitude of the arterial blood pressure, P_{mi} parameter in accordance with the following expression:

$P_{mi} = P_o + P_{mml}$

$$P_{mmi} = K_4 \left[\frac{\Delta V_i}{\Delta \dot{V}_{imax} [G(t)]} \right]^{-b_3}$$

where

k_4 = constant determined for each subject

b_3 = constant

P_{mmi} = pseudo mean arterial blood pressure during cycle i

ΔV_i = maximum volume change during cycle i

$\Delta \dot{V}_{imax}$ = maximum time rate of change of V_i

= $\dot{V}_{imax}$

P_o = constant

$G(t)$ = a function of t and T.

11. Apparatus for determining the magnitude of heart-related parameters in a patient; comprising;

means for detecting blood volume, and thereby blood volume variation, in said patient, and for providing a signal representative of said blood volume, and thereby said blood volume variation;

said means for detecting being attachable to said patient to thereby detect said blood volume, and thereby said blood volume variation;

said blood volume variation being cyclic in nature whereby said signal comprises a cyclic curve having, in each cycle of variation, a variable slope, a maximum amplitude representative of the maximum amount of blood volume, a minimum amplitude representative of the minimum amount of blood volume, a first time interval between said minimum amplitude and said maximum amplitude, a maximum rate of change of said signal being representative of the maximum rate of increase of blood volume, a second time interval between the minimum amplitude and the time of the maximum rate of change of said signal, a first difference in amplitude between said maximum amplitude and said minimum amplitude, a second difference in amplitude between the maximum amplitude and the amplitude at the time of maximum rate of

change of said signal being representative of the difference in volume between the maximum amount of blood volume and the volume at the time of maximum rate of change of said blood volume, and a pulse repetition period;

means for measuring said maximum amplitude, said minimum aplitude, said maximum rate of change of said signal, said first difference, said second different, said first time interval, and said second time interval; and

means for calculating the magnitude of selected ones of said parameters, said means for calculating being connected to both said means for detecting and means for measuring;

wherein means for calculating calculates the magnitude of the pulse pressure parameter in accordance with the following expression:

$$P_{pi} = K_{pp} \left(\frac{R_{i1} - r_1}{(1 + r_2 - R_{i1})} \right)$$

wherein

P_{pi} = pulse pressure during cycle i

K_{pp} = constant determined by a first calibration

r_1 = constant

r_2 = constant

$$R_{i1} = \frac{\Delta V_{i\dot{v}_m}}{\Delta V_i}$$

where

$\Delta V_{i \dot{v}_m}$ = volume change at preselected time $t_{i v_m}$ during cycle i

ΔV_i = maximum volume change during cycle i

$\Delta t_{i \dot{v}_m}$ = time interval from start of cycle i to preselected time of $t_{i v_m}$.

12. A method for determining the magnitude of heart-related parameters in a patient; comprising:

detecting blood volume, and thereby blood volume variation, in said patient and providing a signal representative of said blood volume, and thereby said blood volume variation;

said blood volume variation being cyclic in nature whereby said signal comprises a cyclic curve having, in each cycle of variation, a variable slope, a maximum amplitude representative of the maximum amount of blood volume, a minimum amplitude representative of the minimum amount of blood volume, a first time interval between said maximum amplitude and said minimum amplitude, a maximum rate of change of said signal being representative of the maximum rate of change of blood volume, a second time interval between the minimum amplitude and the time of the maximum rate of change of said signal, a first difference in amplitude between said maximum amplitude and said minimum amplitude, a second difference in amplitude between the maximum amplitude and the amplitude at the time of maximum change of rate of said signal being representative of the difference in volume between the maximum amount of blood volume and the volume at the time of maximum rate of change of said blood volume, and a pulse repetition period;

measuring said maximum amplitude, said minimum amplitude, said maximum rate of change of said signal, said first difference, said second difference, said first time interval, and said second time interval; and

calculating the magnitude of the pulse pressure parameter in accordance with the following expression:

$$P_{pi} = K_{pp} \left[\frac{R_{i1} - r_1}{(1 + r_2 - R_{i1})} \right]$$

wherein

P_{pi} = pulse pressure during cycle i

K_{pp} = constant determined by a first calibration

r_1 = constant
r_2 = constant

$$R_{il} = \frac{\Delta V_{i\dot{V}m}}{V_i}$$

where

$\Delta V_{i\dot{V}m}$ = volume change at preselected time t_{iVm} during cycle i

ΔV_i = maximum volume change during cycle i

Δt_{iVm} = time interval from start of cycle i to predetermined time of t_{iVm}.

13. Apparatus for determining the magnitude of heart-related parameters in a patient; comprising;

means for detecting blood volume, and thereby blood volume variation, in said patient, and for providing a signal representative of said blood volume, and thereby said blood volume variation;

said means for detecting being attachable to said patient to thereby detect said blood volume, and thereby said blood volume variation;

said blood volume variation being cyclic in nature whereby said signal comprises a cyclic curve having, in each cycle of variation, a variable slope, a maximum amplitude representative of the maximum amount of blood volume, a minimum amplitude representative of the minimum amount of blood volume, a first time interval between said minimum amplitude and said maximum amplitude, a maximum rate of change of said signal being representative of the maximum rate of increase of blood volume, a second time interval between the minimum amplitude and the time of the maximum rate of change of said signal, a first difference in amplitude between said maximum amplitude and said minimum amplitude, a second difference in amplitude between the maximum amplitude and the amplitude at the time of maximum rate of change of said signal being representative of the difference in volume between the maximum amount of blood volume and the volume at the time of maximum rate of change of said blood volume, and a pulse repetition period;

means for measuring said maximum amplitude, said minimum amplitude, said maximum rate of change of said signal, said first difference, said second different, said first time interval, and said second time interval; and

means for calculating the magnitude of selected ones of said parameters, said means for calculating being connected to both said means for detecting and means for measuring;

wherein the means for calculating calculates the magnitude of the mean pressure parameter in accordance with the following expression:

1) $P'_{mi} = K_1 r_{ic}^{a}$

where

K_1 = calibration constant

$$P'_{mi} = \frac{P_s + P_d}{2} - P_o$$

P_{si} = systolic blood pressure, in cycle i

$$P_{mi} = \frac{P_s + P_d}{2}$$

P_{di} = diastolic blood pressure, in cycle i

a = constant

P_o = constant.

14. A method for determining the magnitude of heart-related parameters in a patient; comprising:

detecting blood volume, and thereby blood volume variation, in said patient and providing a signal representative of said blood volume, and thereby said blood volume variation;

said blood volume variation being cyclic in nature whereby said signal comprises a cyclic curve having, in each cycle of variation, a variable slope, a maximum amplitude representative of the maximum amount of

blood volume, a minimum amplitude representative of the minimum amount of blood volume, a first time interval between said maximum amplitude and said minimum amplitude, a maximum rate of change of said signal being representative of the maximum rate of change of blood volume, a second time interval between the minimum amplitude and the time of the maximum rate of change of said signal, a first difference in amplitude between said maximum amplitude and said minimum amplitude, a second difference in amplitude between the maximum amplitude and the amplitude at the time of maximum change of rate of said signal being representative of the difference in volume between the maximum amount of blood volume and the volume at the time of maximum rate of change of said blood volume, and a pulse repetition period; measuring said maximum amplitude, said minimum amplitude, said maximum rate of change of said signal, said first difference, said second difference, said first time interval, and said second time interval; and calculating the magnitude of mean pulse pressure in accordance with the following expression:

1) $P'_{mi} = K_1 r^a_{ic}$

where

K_1 = calibration constant

$$P'_{mi} = \frac{P_s + P_d}{2} - P_o$$

P_{si} = systolic blood pressure, in cycle i

$$P_{mi} = \frac{P_s + P_d}{2}$$

P_{di} = diastolic blood pressure, in cycle i

a = constant

P_o = constant

15. Apparatus for determining the magnitude of heart-related parameters in a patient; comprising;

means for detecting blood volume, and thereby blood volume variation, in said patient, and for providing a signal representative of said blood volume, and thereby said blood volume variation;

said means for detecting being attachable to said patient to thereby detect said blood volume, and thereby said blood volume variation;

said blood volume variation being cyclic in nature whereby said signal comprises a cyclic curve having, in each cycle of variation, a variable slope, a maximum amplitude representative of the maximum amount of blood volume, a minimum amplitude representative of the minimum amount of blood volume, a first time interval between said minimum amplitude and said maximum amplitude, a maximum rate of change of said signal being representative of the maximum rate of increase of blood volume, a second time interval between the minimum amplitude and the time of the maximum rate of change of said signal, a first difference in amplitude between said maximum amplitude and said minimum amplitude, a second difference in amplitude between the maximum amplitude and the amplitude at the time of maximum rate of change of said signal being representative of the difference in volume between the maximum amount of blood volume and the volume at the time of maximum rate of change of said blood volume, and a pulse repetition period;

means for measuring said maximum amplitude, said minimum amplitude, said maximum rate of change of said signal, said first difference, said second different, said first time interval, and said second time interval; and

means for calculating the magnitude of selected ones of said parameters, said means for calculating being connected to both said means for detecting and means for measuring;

wherein the means for calculating calculates implicitly the magnitude of the mean pulse pressure in accordance with the following expression:

$$K_3 \left(\frac{e^{-k(P_{mo}-j\emptyset_{1i})} - e^{-k(P_{mo}+j\emptyset_{2i})}}{e^{-k(P_{mo}-\emptyset_{1i})} - e^{-k(P_{mo}+\emptyset_{2i})}} \right) = r_i$$

where

P_{mo} = constant at calibration

$\emptyset_{1i} + \emptyset_{2i} = PP_i$ = pulse pressure during cycle i

k = constant

j = constant

$P_{si} = P_{mo} + \emptyset_{2i} + P_o$

$P_{di} = P_{mo} - \emptyset_{1i} + P_o$

$$P_{mi} = \frac{P_{si} + P_{di}}{2}$$

P_o = constant

r_i = ratio of exponentials

K_3 = coefficient (variable or constant).

16. A method for determining the magnitude of heart-related parameters in a patient; comprising:

detecting blood volume, and thereby blood volume variation, in said patient and providing a signal representative of said blood volume, and thereby said blood volume variation;

said blood volume variation being cyclic in nature whereby said signal comprises a cyclic curve having, in each cycle of variation, a variable slope, a maximum amplitude representative of the maximum amount of blood volume, a minimum amplitude representative of the minimum amount of blood volume, a first time interval between said maximum amplitude and aid minimum amplitude, a maximum rate of change of said signal being representative of the maximum rate of change of blood volume, a second time interval between the minimum amplitude and the time of the maximum rate of change of said signal, a first difference in amplitude between said maximum amplitude and said minimum amplitude, a second difference in amplitude between the maximum amplitude and the amplitude at the time of maximum change of rate of said signal being representative of the difference in volume between the maximum amount of blood volume and the volume at the time of maximum rate of change of said blood volume, and a pulse repetition period;

measuring said maximum amplitude, said minimum amplitude, said maximum rate of change of said signal, said first difference, said second difference, said first time interval, and said second time interval; and

wherein the means for calculating calculates implicitly the magnitude of mean pulse pressure in accordance with the following expressure:

$$K_3 \left(\frac{e^{-k(P_{mo}-j\emptyset_{1i})} - e^{-k(P_{mo}+j\emptyset_{2i})}}{e^{-k(P_{mo}-\emptyset_{1i})} - e^{-k(P_{mo}+\emptyset_{2i})}} \right) = r_i$$

where

P_{mo} = constant at calibration

$\emptyset_{1i} + \emptyset_{2i} = PP_i$ = pulse pressure during cycle i

k = constant

j = constant

$P_{si} = P_{mo} + \emptyset_{2i} + P_o$

$P_{di} = P_{mo} - \emptyset_{1i} + P_o$

$$P_{mi} = \frac{P_{si} + P_{di}}{2}$$

P_o = constant
r_l = ratio of exponentials
k_3 = coefficient (variable or constant).

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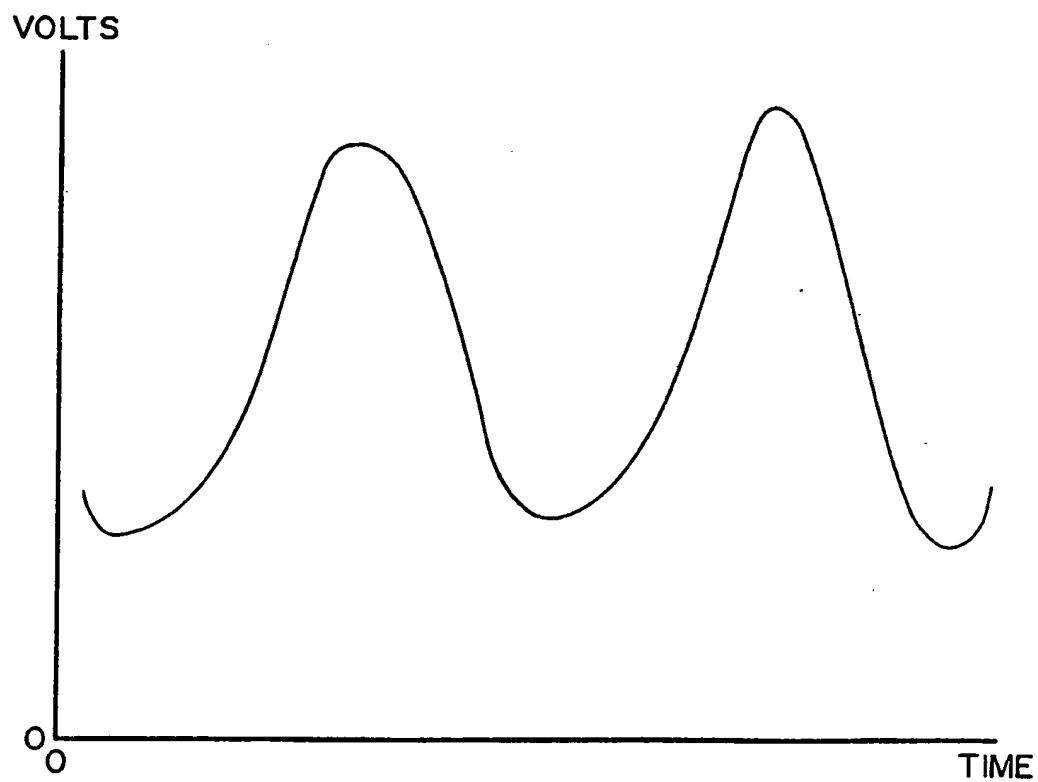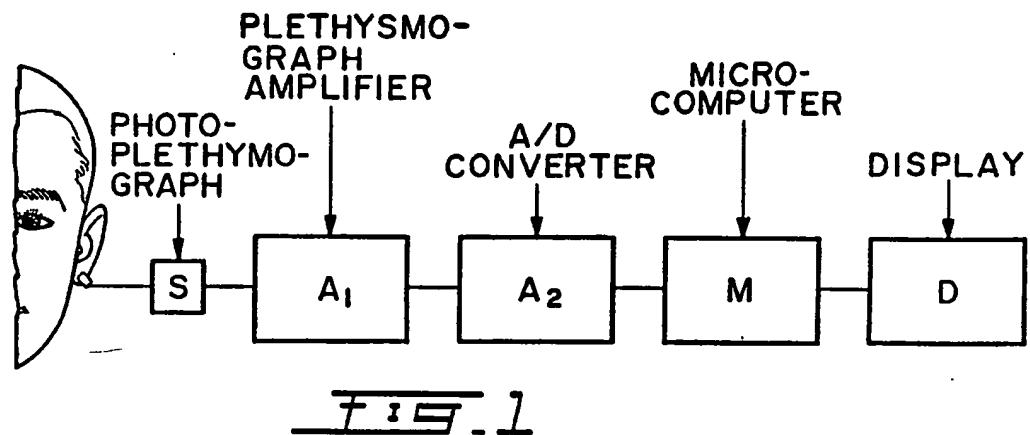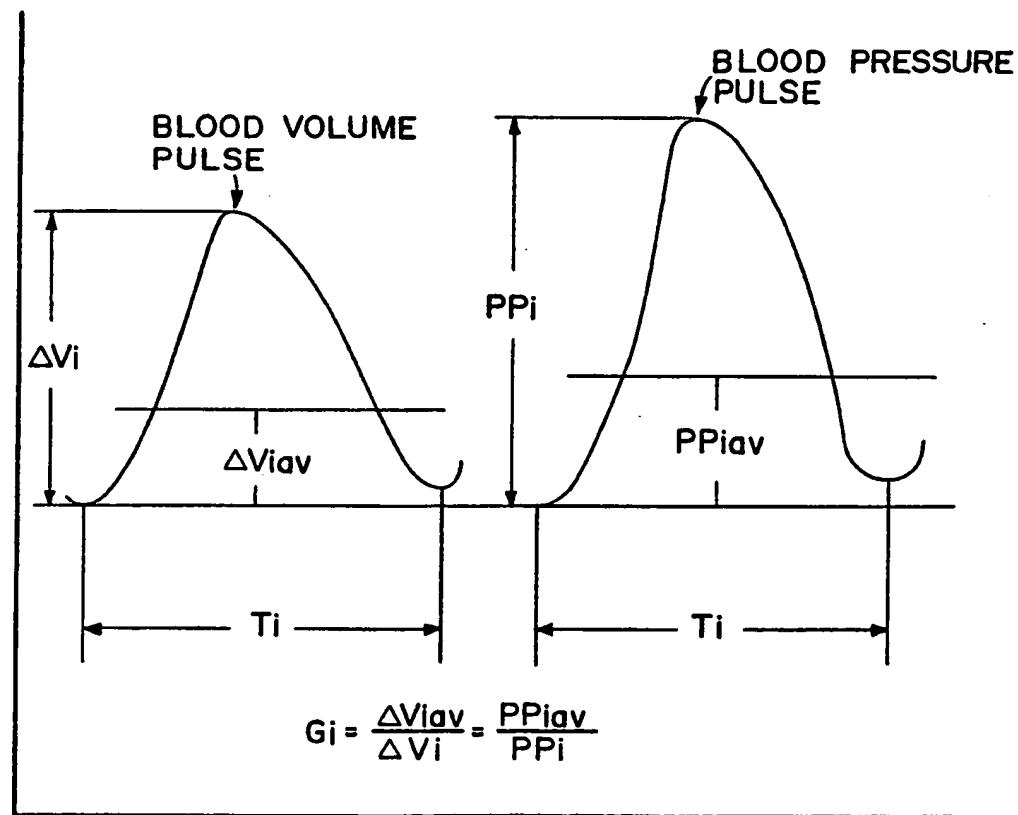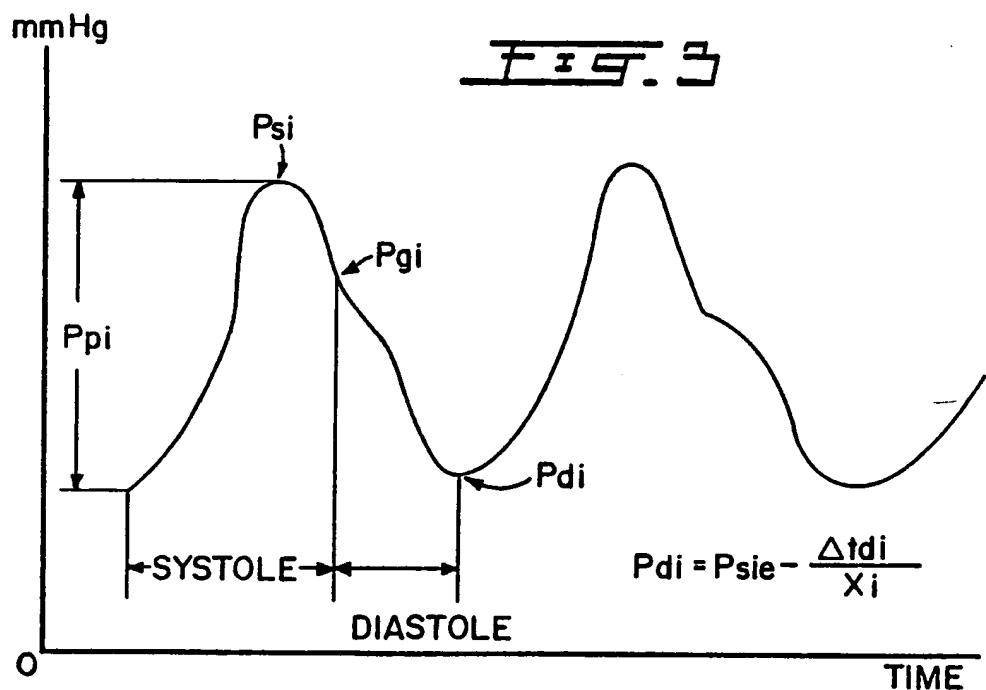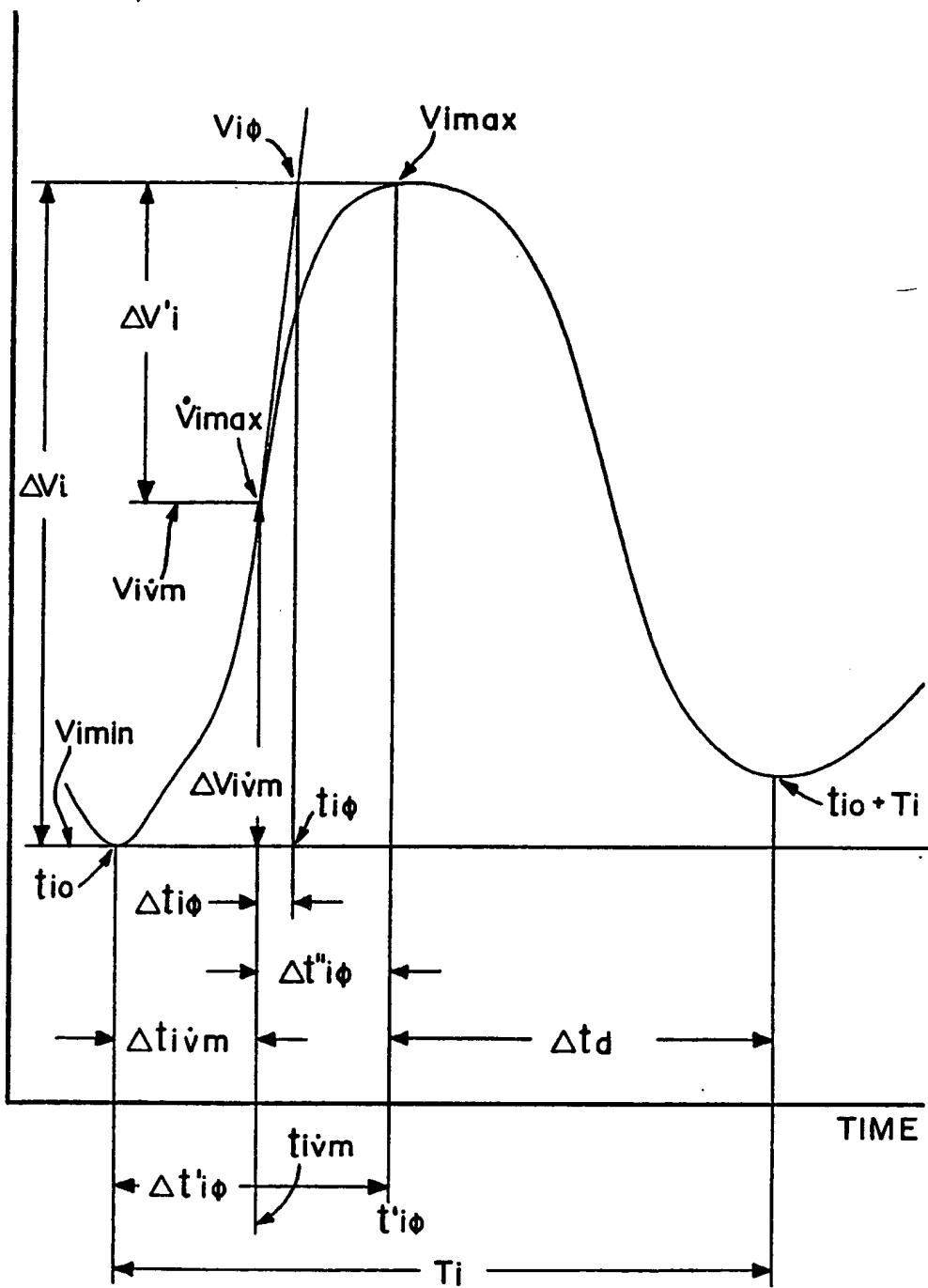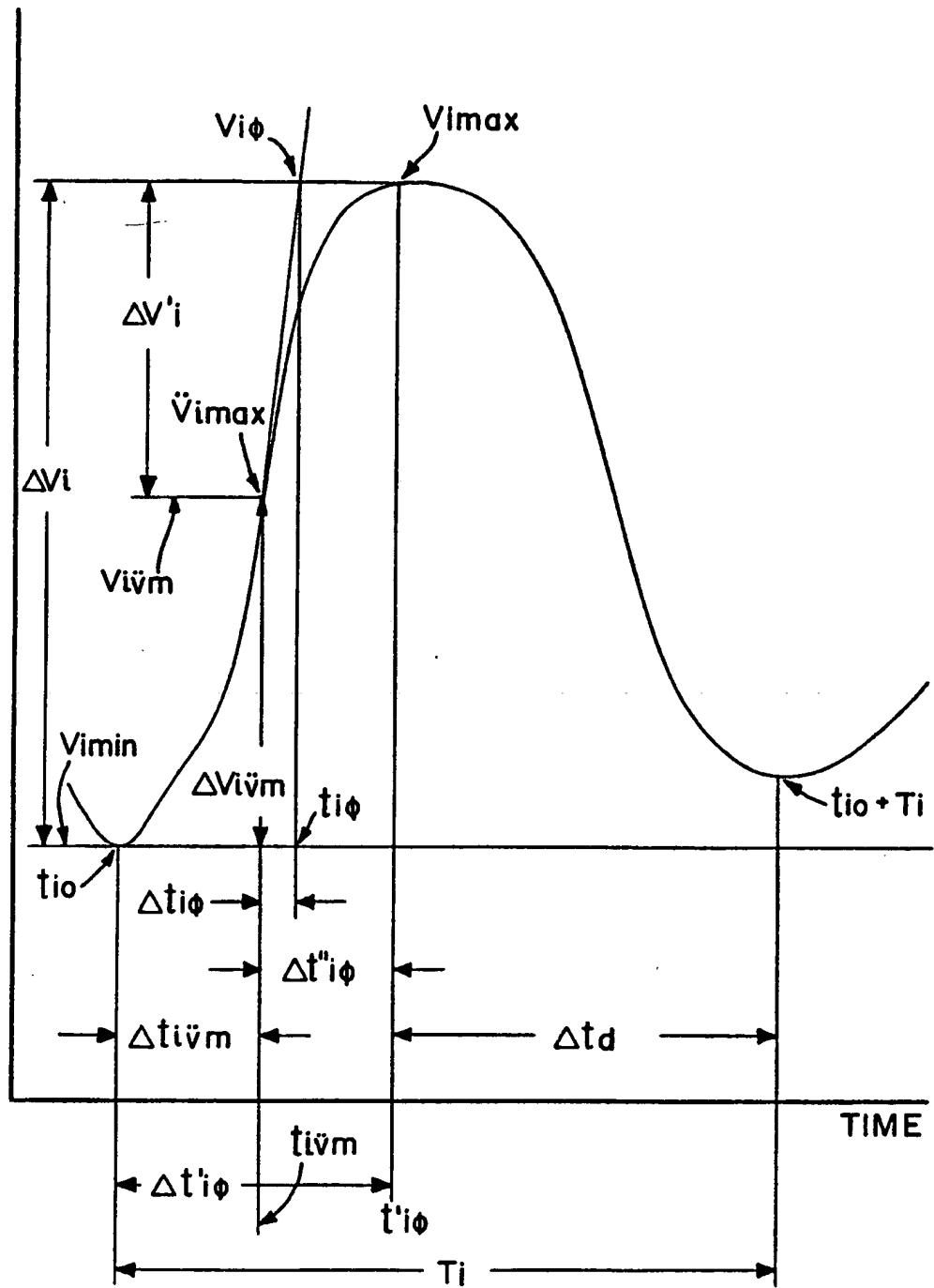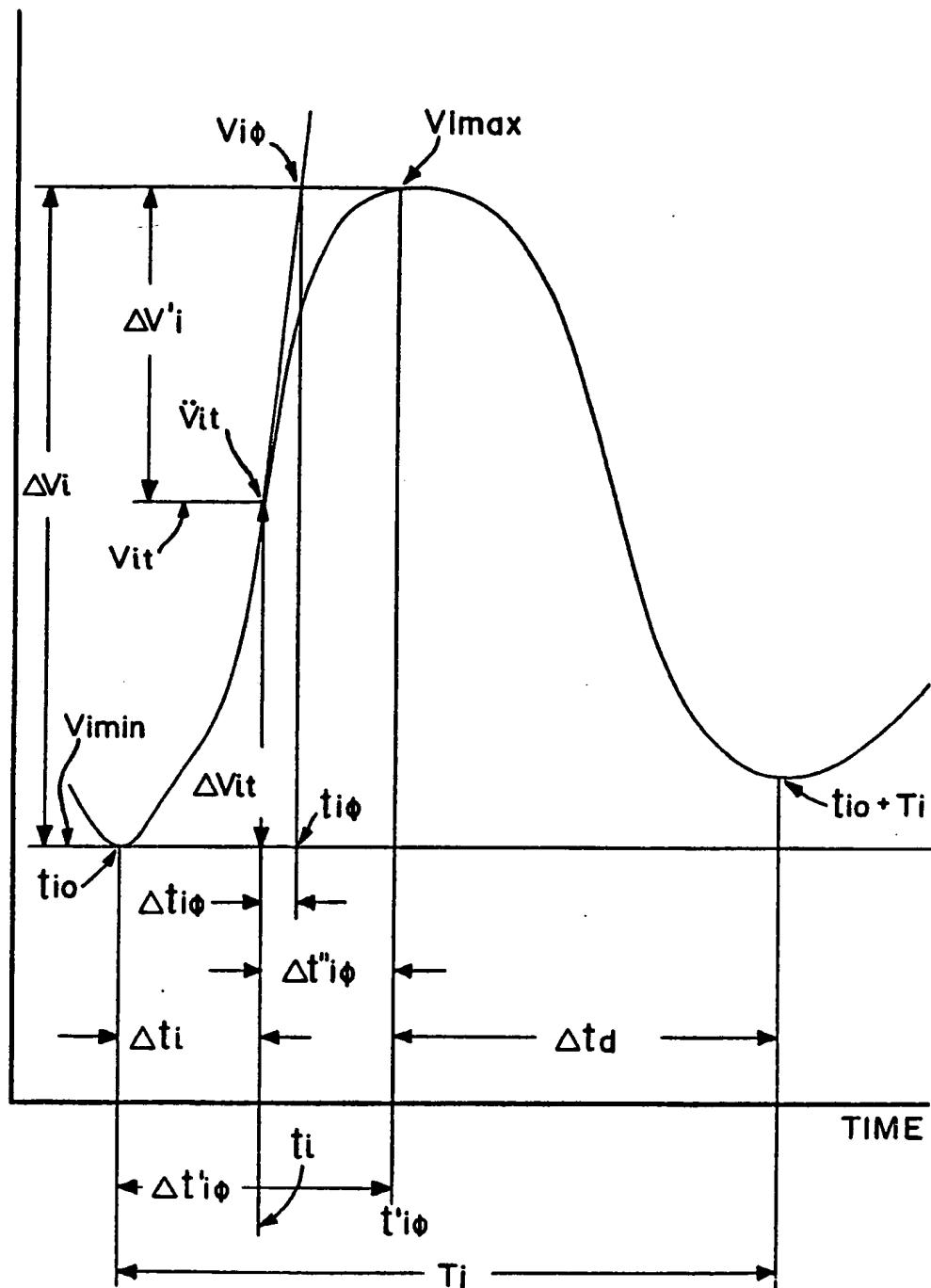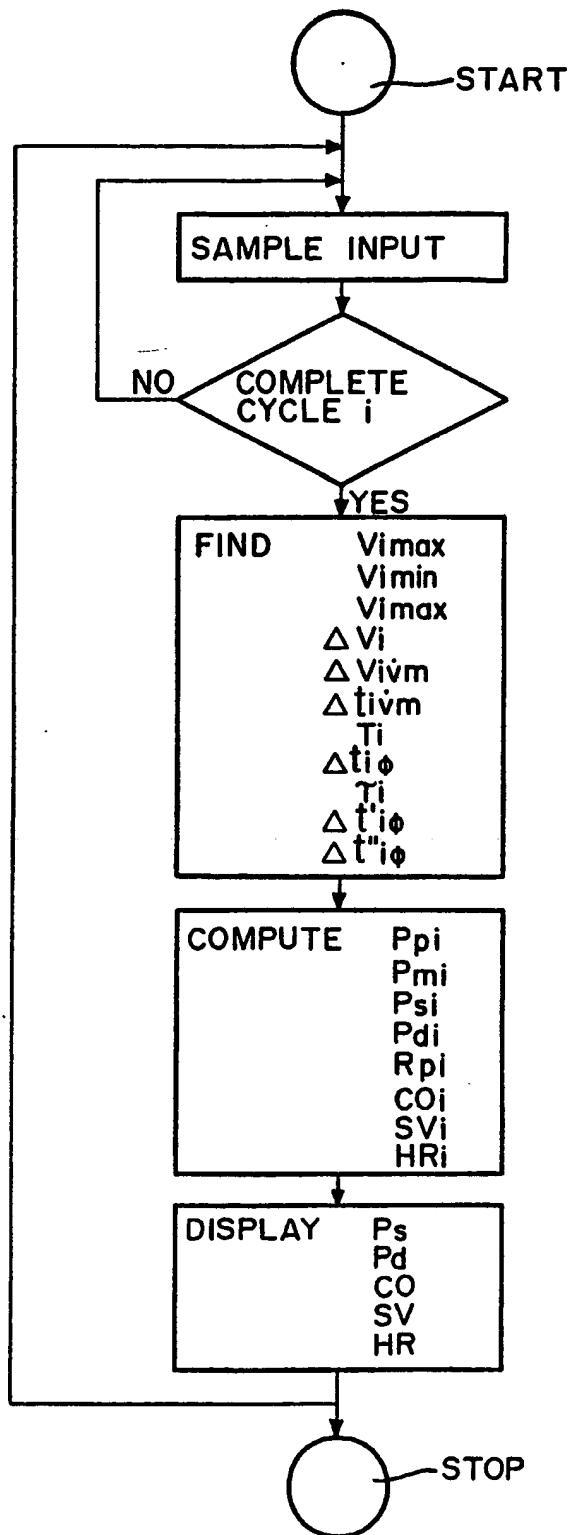
PLETHYSMO-
GRAPH
AMPLIFIER

PHOTO-
PLETHYMO-
GRAPH

MICRO-
COMPUTER

A/D
CONVERTER

DISPLAY

S   A₁   A₂   M   D

FIG.1

VOLTS

0
O   TIME

FIG. 2

mm Hg

$$\text{F I G. } 3$$

Psi

Pgi

Ppi

Pdi

SYSTOLE

DIASTOLE

$$Pdi = Psie - \frac{\Delta tdi}{Xi}$$

TIME

O

BLOOD VOLUME
PULSE

BLOOD PRESSURE
PULSE

ΔVi

PPi

ΔViav

PPiav

Ti

Ti

$$Gi = \frac{\Delta Viav}{\Delta Vi} = \frac{PPiav}{PPi}$$

$$\text{F I G. } 5$$

$Fig.4$

Fig. 4A

FIG.4B

START

SAMPLE INPUT

COMPLETE CYCLE i

NO

YES

FIND   Vimax
        Vimin
        Vimax
        $\triangle$ Vi
        $\triangle$ Viv̇m
        $\triangle$ tiv̇m
        Ti
        $\triangle$ ti$_\phi$
        Ti
        $\triangle$ t'i$_\phi$
        $\triangle$ t"i$_\phi$

COMPUTE   Ppi
          Pmi
          Psi
          Pdi
          Rpi
          COi
          SVi
          HRi

DISPLAY   Ps
          Pd
          CO
          SV
          HR

STOP

FIG. 6

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.5)
X	EP-A-0 160 994 (S. WARNER et al.) * claims 1,3-6,9-11,14-17; figure 1 * ---	1-12	A 61 B 5/02 G 06 F 15/20
A	GB-A-1 538 695 (BIOTRON MEDICAL PRODUCTS LTD.) * page 20, line 30 - page 21, line 12 * ---	1	
A	US-A-4 667 680 (D. M. ELLIS) * abstract; figure 3 * ---	1	
A,D	EP-A-0 060 116 (S. WARNER et al.) * page 1, line 23 - page 2, line 1; figures 1,2 * -----	1	

TECHNICAL FIELDS SEARCHED (Int. Cl.5)
A 61 B 5/00   G 06 F 15/00

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
BERLIN	29-11-1989	WEIHS J.A.

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons

& : member of the same patent family, corresponding document

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